

A SAMPLING PROCEDURE FOR MEASURING INDUSTRIAL DUST EXPOSURE

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In the investigation of pneumoconiosis among workmen exposed to a dust hazard it is necessary to relate the development and progression of the disease over a number of years to the amount of dust in the air which the men breathe. In particular, it is necessary to relate the medical findings to the total dose of dust received by the workman during his time of exposure, for the effect of a given dust on the lungs must depend on the total amount inhaled and retained. It is our purpose in this paper to discuss the problems that arise in measuring the dose of dust, and to suggest a simple method by which they may be overcome. We shall deal specifically with dust sampling in coal mines, but we believe the same principles will hold in other industries.

The difficulties that arise when dust sampling results are to be related to the incidence of pulmonary disease in a defined population are of two distinct kinds. The one results from the variability of the concentration of airborne dust in the environment, the other from the necessity of turning measured concentrations into measures of dosage which may fairly be compared with indices of disease. There has been a tendency in the past to ignore both these sources of difficulty. Bloomfield (1933) and Dallavalle (1940) point out the necessity of estimating the mean duration of exposure to each type of dusty work, and of weighting the average dust concentrations estimated for each type by these times. However, they used measurements of dust concentrations made at fixed positions assumed to be typical of all working places, and variation in the duration of exposure from man to man was ignored. Other discussions of dust sampling in coal mines (Briscoe, Holt, Spoor, Matthews, and Sanderson, 1943); Monmouthshire and South Wales Coal Owners' Association, 1942, 1943, 1944; National Coal Board, 1949) have been concerned solely with methods of measuring the

concentrations of dust, which, it was assumed, would be directly related to the production of disease without considering the duration of exposure of the men at risk. Bedford and Warner (1943), after a discussion of the difficulties involved in making time studies of the activities of coal face workers, also decided to rely on estimates of the mean level of dustiness. Evidence is given later which suggests that none of these assumptions may safely be made, and the results of attempts to correlate dust concentrations and indices of disease suggest that it is essential to adopt methods which make such assumptions unnecessary and which allow for the difficulties of varying concentrations and times at risk.

It will be seen that the total dose received by one man is given by the product of the mean concentration of respirable dust in each unit volume of air in the environment, the volume of air breathed in each unit of time, and the total duration of exposure. We are forced in practice to assume that the volume of air breathed, on the average, is the same from one group of men to another. The remaining factors will need to be estimated, and it will be necessary to study them in relation to those men, and only those men, who are included in the group studied by the medical survey. We do not need to know the dust concentration at a place where no one works, nor the duration of exposure of a man who is not in the group to which the medical findings apply. Moreover, it is essential that the sampling instrument used should give a measure of the concentration of that part of the dust which can be inhaled and retained by the human lung. The thermal precipitator, which is used in the examples given in this paper, can be made to give a measure of the respirable dust provided only those particles are counted which fall in a limited range of size. Any other type of sampling instrument with the required characteristics could, of course, have been used.

The data required are then the men at risk, the mean concentration of respirable dust in the working places of the men at risk, and the time during which the men are at risk.

The Men at Risk

In general, the medical survey can only usefully concern itself with selected groups of men in which the incidence or progression of pneumoconiosis may fairly be attributed to the dust conditions which are found (Hart and Aslett, 1942 ; Cochrane, 1951). Men will have to be excluded if they have a history of possible dust exposure elsewhere, or of exposure to dust other than that on the coal faces where sampling is carried out (in the screening plant on the surface, for example). It follows that it would be insufficient to estimate the average dose of dust inhaled by all the men in the pit and to compare it with the medical index of prevalence or progression amongst only the selected men. We must confine the dust sampling to places in the mine which are occupied by the men among whom the incidence of disease is to be measured. Similarly, we must establish the duration of exposure of these men and of no others.

The Mean Concentration

The variability of dust concentrations at one point on a coal face is such that within a single shift samples may give dust concentrations varying from near zero to a level two-and-a-half times the mean, even though each sample represents an average of the momentary concentrations occurring during a period of two to 10 minutes. Further, from one shift to another the mean level of dust concentration varies as much as the concentration within a shift. Attempts have been made to relate this variation to observable changes in the environment (ventilation, number of colliers, output, etc.) but without consistent success. It seems likely that it will always be necessary to sample during a substantial number of shifts. It has been found that, taking as many samples as possible during eight to 10 shifts (50 to 100 samples in all), the mean of a characteristic set of results may have a standard error of as much as 25%. The consequences of this are twofold ; the significance of quite large apparent differences in concentration may be left uncertain or, more seriously, the significance may be exaggerated by the failure of the sampling technique to detect all the sources of variation which affect the precision of the mean.

In addition to the variation of concentrations at one place with time, differences also occur from place to place, in particular from one end to another of a coal face. A technique of sampling which has

been widely used is to sample at a single point at the return end of the face, or in the return roadway (Monmouthshire and South Wales Coal Owners Association, 1944 ; National Coal Board, 1949 ; Watson, 1949). It would be expected that concentrations near the air-intake end of the face would be lower than those at the return end, and indeed, in certain exceptionally stable conditions, a steady trend of concentrations along the face has been found which could be related to the number of working places or stints between the sampling point and the intake end. In general, however, conditions are too variable for such a trend to be established, and the possibility of a general law being found which would relate the concentration at any point to that measured at a fixed point seems remote. Thus the "return end" sampling procedure is inadequate for estimating the mean concentration to which all the colliers are exposed, and it follows that on each coal face a complete programme of sampling must be undertaken at each collier's working place, or at a sample of them sufficient to establish a precise mean. An illustration of the way in which return-end sampling may lead to misleading results is given later in this paper.

The Time at Risk

Coal-mining is not carried on with the routine regularity of many industrial occupations. The total length of shift, from the time the collier leaves the pit bottom to the time he returns to it, is usually fixed, but the duration of exposure to dust concentrations is as variable as the concentrations themselves. The time taken to reach the face from the pit bottom may be 10 minutes or 50 ; the time taken to get the agreed quantity of coal depends on the practical difficulties encountered from day to day, such as conveyor breakdowns and adverse roof conditions, and the mid-shift break may last anything from 10 to 40 or more minutes. When work ceases on the face, dust concentrations fall very rapidly to insignificant levels, so that periods of temporary stoppage may have to be considered as outside the time of dust exposure.

What allowance is made for these factors must depend on the way samples are taken during a shift. If a continuous sampling instrument were available, many of these difficulties would not arise. At present, the only instruments which are in use sample intermittently. If samples are taken with such an instrument only during "typical" conditions of dust production, then a complete time study of activities on the face must be undertaken so that the period over which the samples are valid may be known. This will involve a series of records as extensive as those of the dust samples themselves.

Alternatively, the samples may be taken at regular intervals throughout the shift or at times chosen previously by a random method. In this case details will still be required of the total time spent on the face, and, in addition, of the duration of the mid-shift break. This will be necessary because samples falling within the break must be treated separately from the rest, for several reasons, among which are difficulties of analysis caused by a number of exceptionally low concentrations.

A particular difficulty is the definition of the exact moment when the shift begins. This arises even if a continuous sampler is used. During the first quarter of an hour men will be arriving, taking up their places, and starting work, and dust concentrations may be abnormal. It is difficult to decide whether sampling should begin when the first man reaches the face, when the last man begins work, or at some intermediate moment. It might be thought that this difficulty is trivial, but these 15 minutes of exceptional conditions (and a corresponding period at the end of the shift) may form a substantial proportion of the total time of dust exposure, which is seldom more than 350 minutes, and has been found in one exceptional mine to be as little as 120 minutes.

Absenteeism is another source of variation in the duration of exposure, and it may also lead to changes in the dust concentrations to which men remaining at work are exposed. With fewer men at work on a face dust concentrations would be expected to be lower than usual. Substitutes are usually brought in to fill the places of the missing men, however. On occasions so many men may be absent that it becomes necessary to close one face for a shift and to transfer the remaining men to another face. Concentrations on the working face may then be higher than usual. In such circumstances it is difficult to decide what weight any samples taken should carry in determining the mean dose.

In practice a complete programme of time study of the collier's working life would be necessary if proper use were to be made of the results of dust sampling by present methods. Moreover, the effort put into dust sampling would not be used as efficiently as it might be unless the results of the time studies were available beforehand to suggest the proper distribution of the work. Obviously, concentrations to which a man is exposed for short periods only need not be measured with the same accuracy as those to which he is frequently exposed.

Practical Illustrations of Conventional Methods

We have suggested a number of difficulties which may be encountered in the course of an attempt to correlate

dust and disease. It could be argued that in practice such difficulties are of small importance, and that the conventional methods of dust sampling are perfectly adequate.

A sampling method which is commonly used at present consists of taking return-end samples at different faces and on different shifts. The results are averaged, and the resulting figure is taken to represent the dust hazard to which the colliers are exposed.

Let us suppose that at two collieries, A and B, return-end dust samples have been collected. It is found that the mean concentration at colliery A is 3,000 particles/ml., and at colliery B, 1,000 particles/ml. Before it can be stated that the dust hazard at colliery A is three times that at B it must first be established beyond reasonable doubt that the men at colliery A have in fact been exposed to three times as much dust as those at colliery B.

The collieries each have two faces. At colliery A face A.1 has full dust suppression and a return-end concentration of 1,000 particles/ml., while face A.2 is a development face without dust suppression, and the return-end concentration is 5,000 particles/ml. Face A.1 is 200 yards long and face A.2 is 50 yards long. At colliery B both faces are equal in length, have full dust suppression, and each has a concentration of 1,000 particles/ml. It is clear that at colliery A the majority of the men are on face A.1 and are exposed to the lower average concentration. There are usually 50 colliers on A.1 and only 10 men on A.2. Assuming for the moment that return-ends are representative of the whole face then a better estimate of the mean concentration to which the 60 colliers are exposed is:

$$\frac{(50 \times 1,000) + (10 \times 5,000)}{60} = 1,667 \text{ particles/ml.}$$

and not 3,000 particles/ml., the unweighted mean of the two return-end concentrations.

The respirable fraction of coal dust is nearly all less than 5 microns in diameter. Dust of this size settles out of the air very slowly. At colliery A the loader points, which produce a lot of dust, are in the return airways so that only the dust produced by the colliers themselves is included in the air they breathe. Consequently the first collier from the intake is exposed to very little dust and the dust from subsequent colliers builds up the concentration continuously to the return-end. The average concentration for such a face is thus about half that at the return-end. At colliery B, however, the loader points are in the intake and are very close to the face. A considerable quantity of fine dust is carried from them on to the face and in such a case the return-end may be no more dusty than the average for the whole face. We may conclude therefore that whereas the mean concentration to which the colliers at colliery A are exposed is 1,667/2 or 833 particles/ml., at colliery B the appropriate mean concentration remains at 1,000 particles/ml.

During the two surveys time studies were pursued at the two collieries during the sampling. At colliery A the coal faces are a long way from the shafts but the coal is very easy to get. The total time spent working in dust is just three hours. At colliery B, however, the coal faces are near the shafts and, the coal being very

hard to get, the men are working in dust for the complete seven-and-a-half hours of the shift, or two-and-a-half times as long as the men at colliery A. The total exposure to dust at A is thus $833 \times 3 = 2,500$ particle-hours per shift, and at B is $1,000 \times 7\frac{1}{2} = 7,500$ particle-hours per shift. Consequently there is at colliery A about one-third the amount of dust available for inhalation as there is at colliery B, although the simple averaging of return-end samples led to an exactly opposite conclusion. It is clear that if such dramatic changes can be produced, admittedly in an extreme case, by making allowance for the place of work and duration of exposure of the men at risk, then these factors must be estimated with as much care as the dust concentrations themselves. The rough estimates used in this simplified illustrative example would be inadequate.

Apart from these long-term considerations others arise in actually carrying out a return-end survey, such as the following, which have been encountered in recent surveys by the Pneumoconiosis Research Unit:—(1) Towards the latter part of the shift most of the men at the face had finished their work and left, while a few continued in order to complete their stints. As the men drifted out, so the concentration slowly dropped. When should sampling have ceased? (2) Because of difficulties the day before, the cycle of operations on a face had fallen behind and colliers from elsewhere in the pit were brought in to bring the strength up to double and so rectify the situation. Consequently, dust concentrations were very high and twice as many men were exposed to them. What weight should be given to this day's sampling, in view of the fact that the relative frequency of such exceptional days is not known? (3) A face consisted of a left-hand intake, a leakage return through which half the air passed, and a right-hand return which carried the remainder. Are there two sampling positions on this face? (4) There was a squeeze on the face the night before and the men worked on the roof during the coal-getting shift to open out the workings. What weight should be given to this day's sampling? (5) One seam was working longwall, and the other hand-got pillar and stall. In the pillar and stall workings the ventilation was very sluggish (air velocity less than 30 ft./min.) and the air filtered through many holes and old workings on its way through the seam. The men were working in pairs, scattered over the area. Where should the sampling position be located? (6) New entrants are put on the training face for a short period before proceeding to the main production faces. What weight should be given to samples taken here? (7) A fall of roof occurred in the main gate over a length of 10 yards. The colliers were put on cleaning the rubbish into trams. Should samples be taken and if so where and what weight should be given to them? It should be

remembered that some of these decisions must be taken on the spot by the sampling technicians, and that others may cause considerable difficulty when the results come to be analysed.

The "Random Colliers" Method

The method of sampling we propose, to avoid the difficulties we have illustrated, is simple and economical. This method, which has been called "random colliers", consists of using the movements of individual colliers in the group studied by the medical team to determine the place and duration of dust sampling. Colliers are chosen by a random principle from this group, and, if an intermittent sampling instrument is being used, samples are then taken at the working places of each man at moments also chosen at random. The number of colliers followed in this way, and the number of samples taken in each working place, is determined by the resources of the sampling team and the fact that for the highest efficiency the maximum number of colliers should be followed. Since, however, practical considerations limit the amount of moving about done by the sampler, the best method appears to require each collier to be followed for one whole shift. Given the number of days which can be spent on the survey, the number of sampling instruments available, and the number of samples which can conveniently be evaluated, the number of colliers chosen and the number of samples per shift are deduced. The method is thus an extension of that proposed by Patterson (1939), in which a dust sampler follows an individual workman throughout his working day. It was clearly implied, though not stated, that this man is taken as typical, i.e. as a random sample of all those to be studied.

The time taken to prepare a complete sampling scheme of this type is no more than an hour or two, and the procedure is straightforward. The sampling itself is free from problems arising out of exceptional conditions, since the chosen collier's exposure provides a constant guide to the sampling procedure.

If automatic, continuous sampling instruments were available each random collier would take one with him from the pit top to his place of work and back again, and the instrument would sample continuously throughout his dust exposure. A satisfactory instrument of this kind must clearly be as portable and convenient as, for example, a Davy lamp.

It must be shown how this simple technique meets the objections and difficulties we have discussed. First, although nothing can eliminate the sampling errors introduced by the high variability of concentrations, it has been pointed out that the most efficient sampling method gives each momentary

state of the environment a weight proportional to its importance to the collier's health. This requirement is fully met by the proposed system, for the probability that a particular concentration is sampled is proportional to the time it endures.

The second difficulty, that of relating concentrations and their duration to obtain the total dose, is also overcome. The problem of deciding when to begin and end sampling, or when to begin and end the period during which samples are to be taken at random times, can be dealt with simply by deciding when the random collier enters and leaves the dusty environment. In principle we are sampling the dust exposure of the random collier throughout his whole day; it is merely fortunate that his exposure begins and ends with his working hours and we are able to concentrate our attention on that period alone. We record its duration, and are then in a position to evaluate the total dose over whatever period is convenient.

Problems raised by absenteeism are similarly overcome. If the chosen man is absent his exposure is nil and no samples are taken. Providing no substitute is sampled instead, no bias is caused by a redistribution of the remaining colliers to fill his place. The unusual conditions so produced have exactly their due chance of being sampled since they may occur when the chosen collier is present and others are absent.

It might be thought that greater accuracy would be attainable if it were arranged that at least one collier from each face was always chosen. This would be a practical method if the number of men working on a face were always the same. In fact this is not so, and the gain in precision which would result from such "stratified" sampling is offset by the increased difficulty of combining the results and making the necessary records. It seems advisable on the whole to adhere to the purely random method we have described in which individual samples are combined in a simple manner, and no problem of differential weighting arises.

The details of the method are most easily shown by means of an example of its use in a survey at a South Wales colliery. Very few complications had to be added in practice to the simple scheme described above.

Practical Example of the "Random Colliers" Method

The men to be studied in this survey were the coal-getters, the colliers actually working on the coal face with their assistants, and the object of the survey was to estimate their exposure to respirable dust of whatever kind. A list of these men was provided by the colliery manager; the total number was 142.

The time to be spent on the survey was limited to two weeks, or 11 coal-getting shifts (the pit was working

alternate Saturdays). Four observers were available, and the sampling instrument to be used was the thermal precipitator.

Since this was to be in some respects an exploratory survey, it was decided to arrange the sampling so that an estimate could be made of the variability of concentrations experienced by an individual from day to day. For this purpose each collier was to be observed on two different shifts. The sampling scheme then depended on distributing the 44 shifts which could be sampled by four observers on 11 working days among 22 randomly chosen colliers. This was done by taking from a table of random numbers the first 22 which were less than 143. The chosen colliers were then those in the list numbered from 1 to 142 whose serial numbers had been selected. By a further use of random numbers a table was drawn up in which four different colliers (one to each observer) were allocated to each of the 11 sampling days, in such a way that each collier appeared on two different days.

The number of thermal precipitator samples that can be taken during a survey is limited by the labour involved in counting the deposits. It was decided in this case that not more than about 450 samples should be taken. Thus about 10 samples were to be taken each shift by each observer, and the maximum was set at 12. The total period of exposure during a shift cannot be predicted with any accuracy, but, in practice, work on the face does not begin before 7.45 a.m. nor end after 2.15 p.m. It could be assumed that at this colliery there was no material dust exposure while travelling from the shaft to the face. To ensure a random distribution of samples throughout the shift, recourse was had again to random numbers, and for each of the 44 shifts a list of 12 times was prepared, lying between 7.45 a.m. and 2.15 p.m. and separated by at least eight minutes (each sample took three minutes, and five minutes was allowed for adjustment of the instrument between samples).

Each observer's daily programme was thus as follows. He met his allocated collier at the lamp-room on the surface or at the deputy's cabin underground, and travelled with him to his place of work. The thermal precipitator was set up, upwind of the collier and at head level, as close to him as could be managed without interfering with his work. The distance was usually about six feet. The first sample was taken at the first time on the prepared list which was after the time of arrival. Successive samples followed until the collier left the face. The time of arrival and departure was noted, and the time and duration of the mid-shift break.

Results

Between the time the sampling scheme was prepared and the beginning of the survey one collier left the pit. Unfortunately he was one of the selected men, and in consequence the sample consisted of 21 men chosen out of 141. One collier was an absentee on both of the days he was due to be observed, and another five were absent on one of their days. Some of the samples taken were lost by contamination, but it has been observed

that such losses are not correlated with the level of the dust concentrations, so that the results are not biased by the loss of some of the data. The full results are given in the appendix table.

The mean concentration to be estimated from the data is that to which the average collier was exposed. The mean concentration to which one collier was exposed will be given by the unweighted mean of the means for each of the days for which he was observed. The final figure will be the mean, again unweighted, of these. This was found to be 716 particles per ml. In this calculation the readings obtained during the mid-shift break, which were all effectively zero, were excluded. We therefore calculated the durations of exposure from the recorded shift lengths, excluding the length of the mid-shift break. These were found to be uncorrelated with the concentrations observed. Thus the mean duration of exposure was taken as the grand mean of all the observed shift lengths less break times, and the figure that resulted was 311 minutes. This, multiplied by the mean concentration, gives 222,676 particle-minutes per ml., or 3,710 particle-hours per ml. Assuming a constant volume of air breathed per minute, and no dust exposure outside working hours, we may conveniently express this figure as proportional to a dose of 3,710 particles each working day.

An analysis of variance was carried out on the data, for which purpose it was necessary to work with the logarithms of the measured concentrations and shift lengths. It was found that significant variation was occurring in the dust concentrations from one collier's experience to another's, and from one day to another in the same collier's experience. Estimates were made of the magnitude of this variation, and of the variation of successive samples taken on the same day, and finally 95% confidence limits were calculated for the dose given above. These were 3140 and 4080.

The greatest practical difficulties found in carrying out the survey came from the use of a short-period sampling instrument. An automatic continuous sampler, operating from the moment the collier entered the mine to the moment he left it, would make it unnecessary to make special provision for the effect of mid-shift break and the irregular shift length. No difficulty was experienced in explaining the idea of "a cross-section of the pit" to the individual colliers chosen, nor did any collier show resentment at being picked out. In fact the individual's usual reaction was one of interest and cooperation, just as has been found by those engaged in carrying out public opinion polls or sample surveys of sickness. There was no sign that he modified his habits of work because of the

presence of the sampling instrument, and it should be remarked that even if he did his exposure would be substantially unaltered; the collier does not breathe his own dust to any material extent, but rather that produced upwind of him by his work-mates.

Long-term Surveys

In conclusion we must refer briefly to the procedure to be adopted in continuing a survey for a long period, or in carrying out a series of short surveys at regular intervals, as will generally be essential in correlating dust exposure with disease. The chief difficulty to be considered is the possibility that the population of the pit may change, some of the original men leaving and new men taking their places. The difficulty may be met by ensuring that the population sampled remains, throughout, the population in which incidence of disease is to be studied.

Example of a Long-term Survey System

One system which would satisfy this requirement may be illustrated by an example. Suppose a colliery which is to be subject to periodical radiographic surveys has initially 200 coal-getters on its books. Each year some of these will leave the colliery or move to jobs away from the face and others will take their places. To the original list of 200 men a number of blanks are added, perhaps 40 if the population of colliers is known to fluctuate in numbers by about 20%. These 240 numbers are put into random order. Then, if 10 sampling instruments are available, the first 10 men on the randomized list form the first random colliers. As men leave their numbers become vacant, and as new men join their names are placed against the first blank spaces on the original list and against the corresponding numbers on the randomized list. In this way sampling is continued, taking always the next 10 occupied numbers on the randomized list. When the end of the list is reached the procedure begins again at the beginning. It will be seen that in this way the probability that a man will be sampled remains, as is necessary, proportional to his time at risk. The method can obviously be extended to cover a series of surveys as well as a continuous one. In general, provided it is possible to deduce a valid measure of disease incidence or progression, a valid measure of dose of dust will be calculable by following a strictly comparable procedure.

Discussion

In this paper we have attempted to show that a proper evaluation of an industrial dust exposure must take into account variations in the concentration of the dust and of the duration of exposure of the men at risk, who must be the same men upon whom the incidence of pneumoconiosis is observed. This must be so whether it is the dose of all respirable dust or of some particular part of the respirable dust (the free silica, for example)

which is to be compared with the incidence of disease.

Methods of sampling that have been employed in the past mostly rest upon the assumption that in the long run the average of a number of dust samples taken on any principle will lead to a quantity which can validly be compared with an observed disease incidence. We have suggested that even if such assumptions are justified, and we have presented some evidence to the contrary, these methods cannot be economical. The concentrations measured by a sampling instrument do not all carry equal weight as measures of the dust hazard; their individual importance must depend on their duration and on the number of workmen exposed to them. This criticism applies even more strongly when care is taken to evaluate durations of exposure by a separate and extensive series of time studies. A random collier survey involving an equal amount of dust sampling makes the most economical use of the labour and time spent, for it automatically gives to each concentration a weight proportional to its importance in producing pneumoconiosis. We may remember here the remark of Belt and Ferris (1942): "The collier's lung is, in a very real sense, his occupational log book; it retains a qualitative and an indelible record of the mineral particles breathed during life." By basing the programme of sampling on the collier's occupational log book, we are imitating with our sampling instrument the experience of his lungs.

Summary

Any method of estimating the dust exposure of workmen for correlation with the incidence of pneumoconiosis must satisfy the following criteria:—

(1) The exposure estimated must be that of the

same workmen upon whom the incidence of pneumoconiosis is to be found. (2) The duration of exposure must be measured as well as the concentration of dust. (3) Account must be taken of the effects of the variability of exposure, both in duration and intensity.

Evidence is produced showing the errors that can arise from ignoring these criteria, and a new method of dust sampling is described which satisfies them. This method is based on following with a sampling instrument throughout their working day individual workmen chosen by a random principle from all those on whom the incidence of disease is to be measured.

A practical example of the use of this method is given, and it is demonstrated that the method is simple to execute and makes the most economical use possible of a given amount of sampling.

We should like to thank our colleagues in the Pneumoconiosis Research Unit for helpful discussions, and the South-Western Division of the National Coal Board for the facilities so readily placed at our disposal.

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APPENDIX

RESULTS OF "RANDOM COLLIERIES" SURVEY

Collier	Total Time Spent on Coal-face (min.)	Duration of Mid-shift Break (min.)	Thermal Precipitator Samples (No. of particles per ml. between 0.5 and 5.0 μ)											
			1,630	800	1,100	920	1,500	1,770	980	1,430	1,540			
1	315 430	25 15	1,630 950	800 <100*	1,100	920	1,500	1,770	980	1,430	1,540			
2	—	—	<i>Collier no longer working at pit</i>											
3	350 365	20 20	<100 800	1,320 1,180	650 1,130	<100 880	<100 430	360 430	(<100)† 390	<100 360	220 460	180 440		
4	345	20	1,750	1,690	2,030	2,730	1,980	940	1,360	2,070	2,190	830	2,650	
5	— —	— —	} <i>Collier absent on both occasions</i>											
6	270 335	20 25	570 240	<100 170	<100 450	(210) 560	310 320	740 280	2,000 (<100)	520 320	520	820	520	510
7	325 365	40 35	390 1,110	700 730	920 (<100)	1,240 (<100)	1,580 750	1,530 1,090	920 720	530 1,130	580	770		
8	300 395	25 25	580 350	770 1,460	470 800	(<100) 1,250	1,150	1,010	(<100)	860	920	760	840	
9	— 375	— 25	<i>Collier absent</i>											
			670	550	480	520	530	450	1,490	950	790	560		
10	375 360	20 35	230 1,450	410 1,100	510 1,020	460 900	490 340	290 270	230 240	270 550	150 260	1,060 380	310	
11	390 380	25 20	2,770 460	4,510 480	2,240 750	280 510	500 (<100)	380 460	400 270	300 410	520	650	780	650
12	375 380	25 25	570 690	470 1,460	490 1,150	470 1,030	500 980	630 350	640 440	710 560	450 2,290	320 810	180 710	1,330
13	‡ —	‡ —	770	650	870	1,280								
			<i>Collier absent</i>											
14	365 345	20 25	330 1,240	530 1,290	430 1,150	(<100) 1,160	640 1,040	620 470	550 760	680 790	720	730	(<100)	1,800
15	380 —	20 —	550	<100	200	130	490	420						
			<i>Collier absent</i>											
16	390 355	25 50	180 170	460 <100	590 480	550 480	370 690	350 (<100)	270 (<100)	290 (<100)	620 (<100)	290 380	250 460	230 400
17	375 355	25 20	580 1,630	940 1,470	660 1,560	920 1,790	760 1,780	760 1,250	750 1,000	790 840	1,230 1,000	1,080 1,870	1,390	900
18	325 375	25 30	<i>Samples contaminated and uncountable</i>											
			920	620	1,010	1,040	980	(<100)	(<100)	530	1,040	870	770	
19	360 330	20 25	690 570	700 800	1,030 710	(<100) (<100)	530 (130)	610 420	510 530	1,060 620	260 520	710	370	<100
20	340 —	15 —	<100	760	2,660	3,680	430	230	120					
			<i>Collier absent</i>											
21	345 —	30 —	1,090	660	540	1,120	840	620	820	710				
			<i>Collier absent</i>											
22	350 380	50 20	570 490	760 370	840 650	690 830	1,370 670	900 640	650 440	660 680	380	400	610	400

* Samples too sparse to count are recorded thus.

† Samples in brackets were obtained during the mid-shift break.

‡ Not recorded.